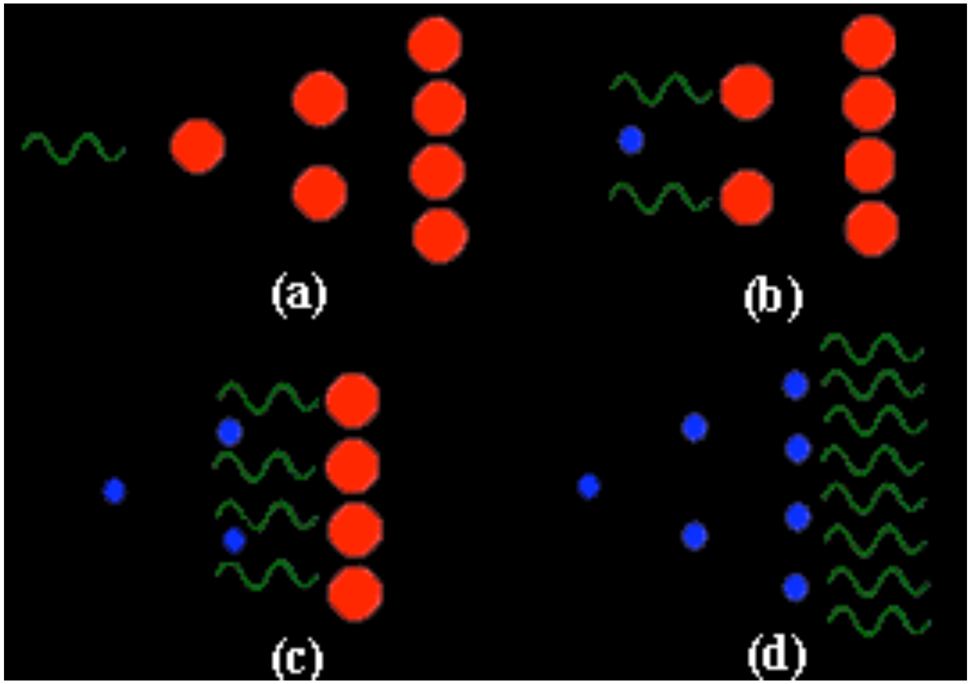
Masers

Donna Kubik

- Why were masers developed before lasers?
- How did the first maser work?
- Applications?
- What was *really* the first maser?

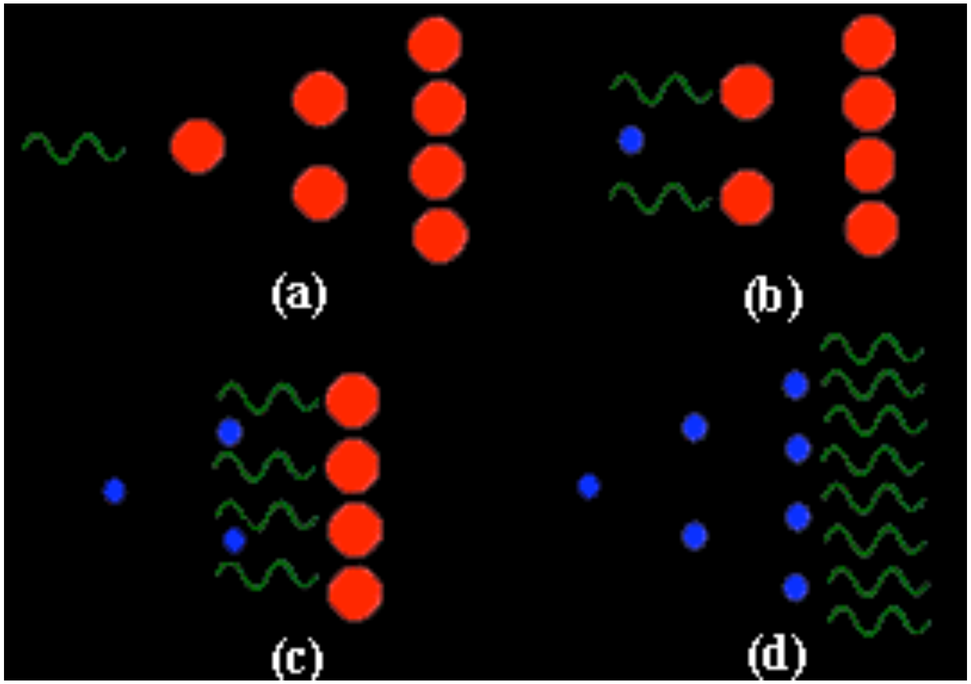


Masers

- Maser
  - microwave amplification by stimulated emission of radiation

- A man-made maser is a device that sets up a series of atoms or molecules and excites them to generate the chain reaction, or amplification, of photons

- Metastable emission states make masers possible

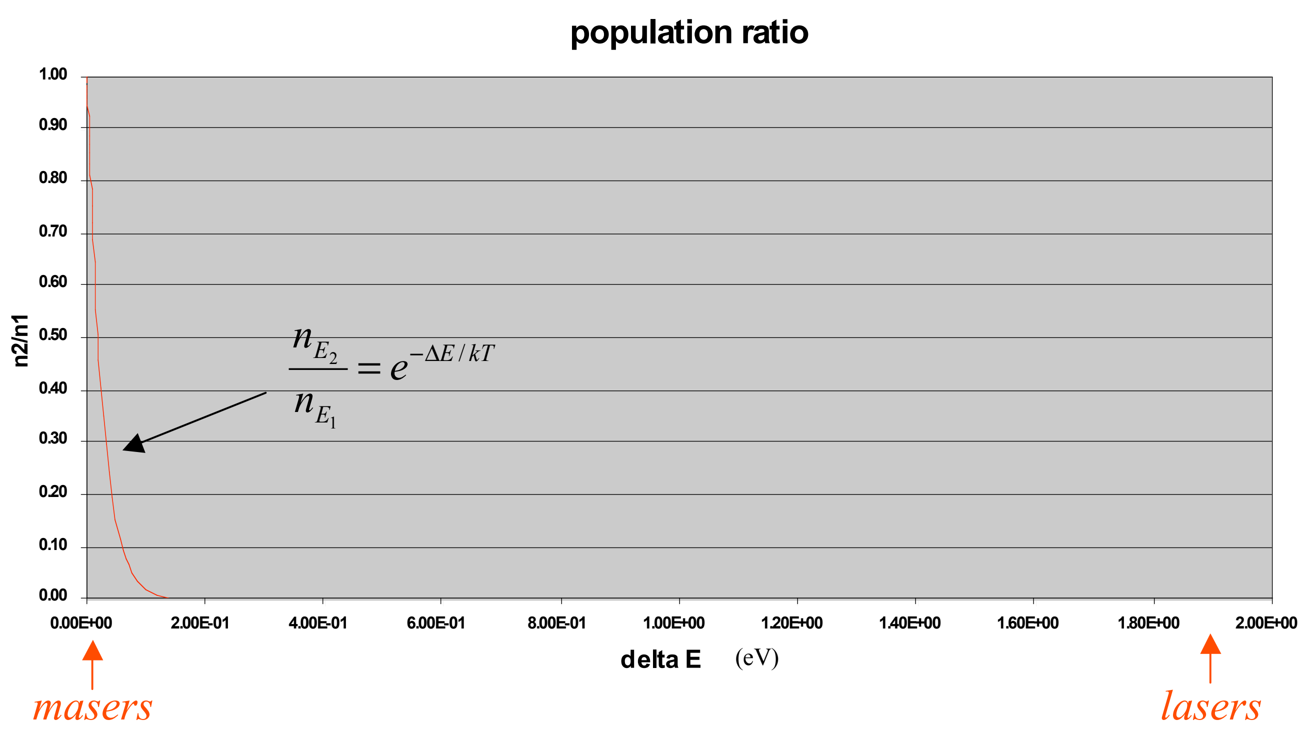


Masers

- It is no coincidence that “laser action” was first produced in the microwave region
  - There is no need for pumping

Population ratio

- The Boltzman distribution may be used
  - The first maser operated with a gaseous system
  - The neither molecular state influences the other state
  - The system is in thermal equilibrium

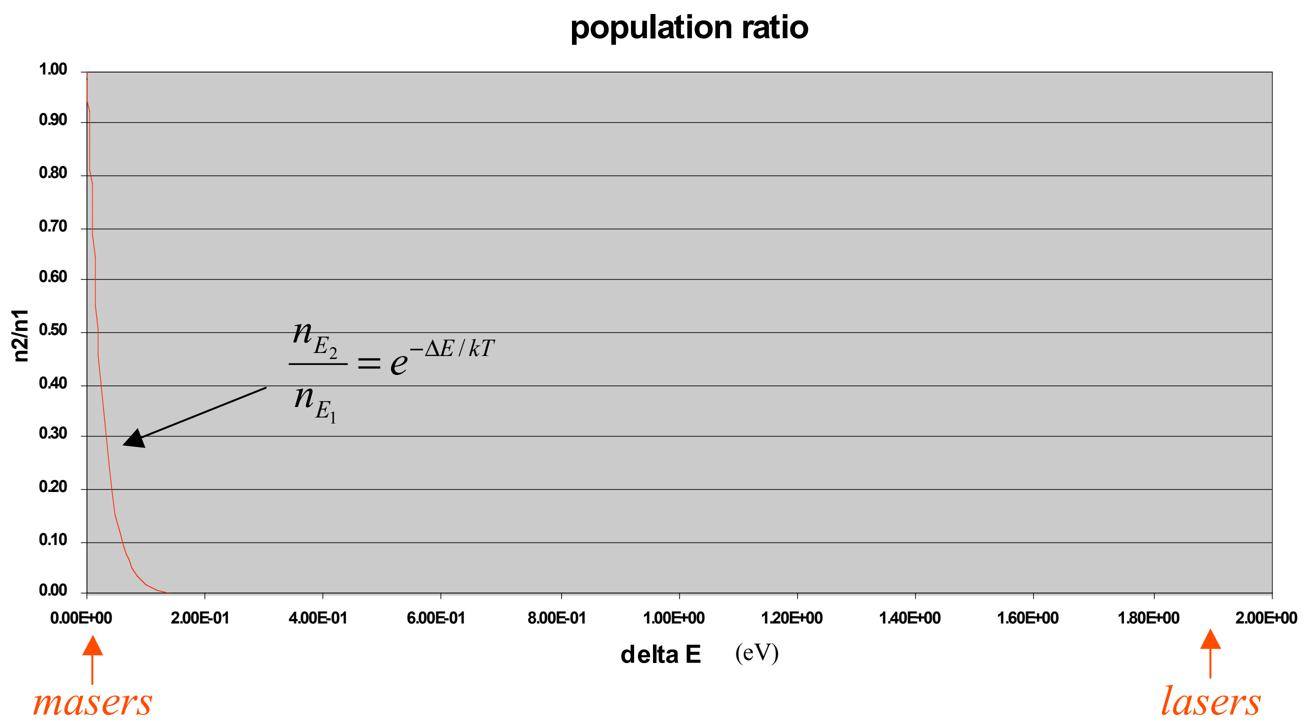


Population ratio

– The population ratio of the higher energy state to the lower energy state is about 1:1 in the energy range that corresponds to microwaves

ΔE for maser is ~10^{-5} eV

ΔE for a laser is a few eV

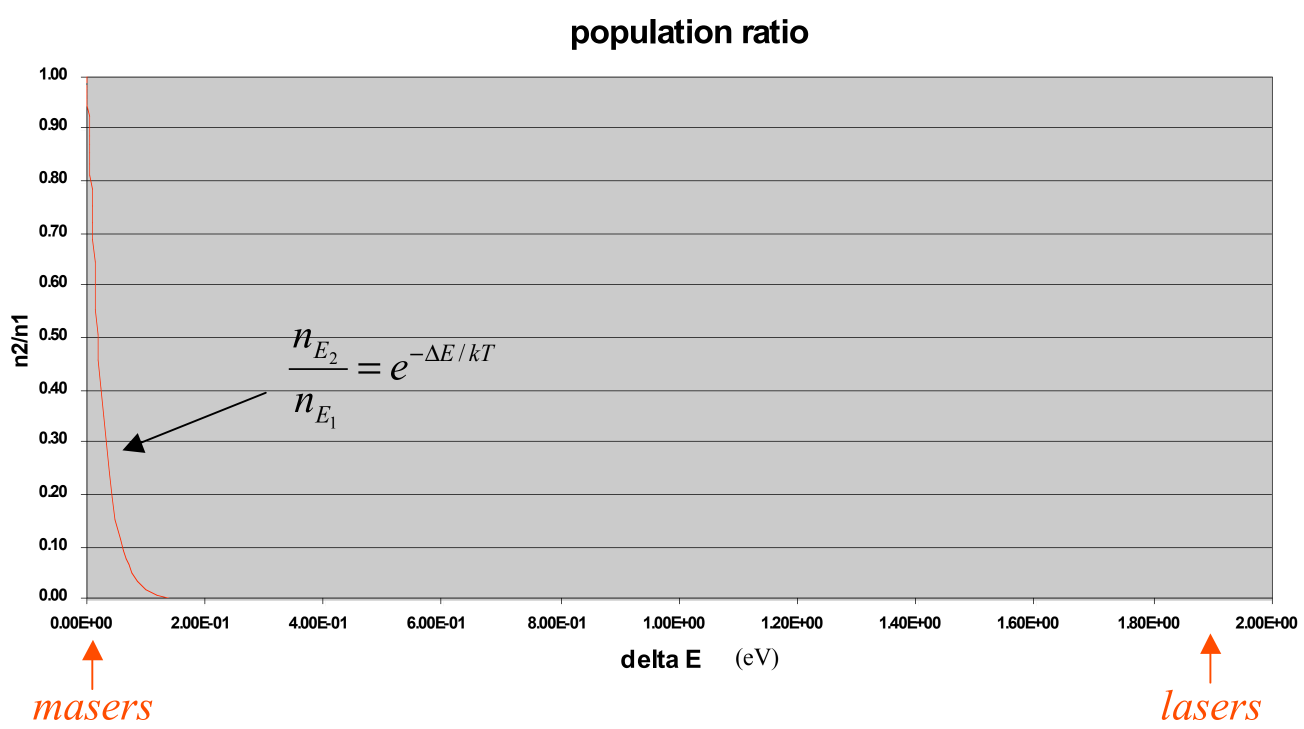


Population ratio

– So thermal energy (kT_{room} = 0.0258eV) is enough to generate a large population of atoms in the higher energy state

ΔE for maser is ~10^{-5} eV

ΔE for a laser is a few eV



Masers

- Another reason it is no coincidence that "laser action" was first produced in the microwave region
  - There is no need use 3 or 4 level schemes to populate a metastable state

Masers

- The ratio of the spontaneous emission coefficient to the stimulated emission coefficient varies with frequency as ν^3
- This ratio is much smaller in the microwave part of the spectrum than in the optical
- Spontaneous emission can therefore be neglected compared to other important processes such as stimulated emission and absorption.

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h \nu^3}{c^3}$$

Masers

- There is no need take advantage of an intermediate metastable state

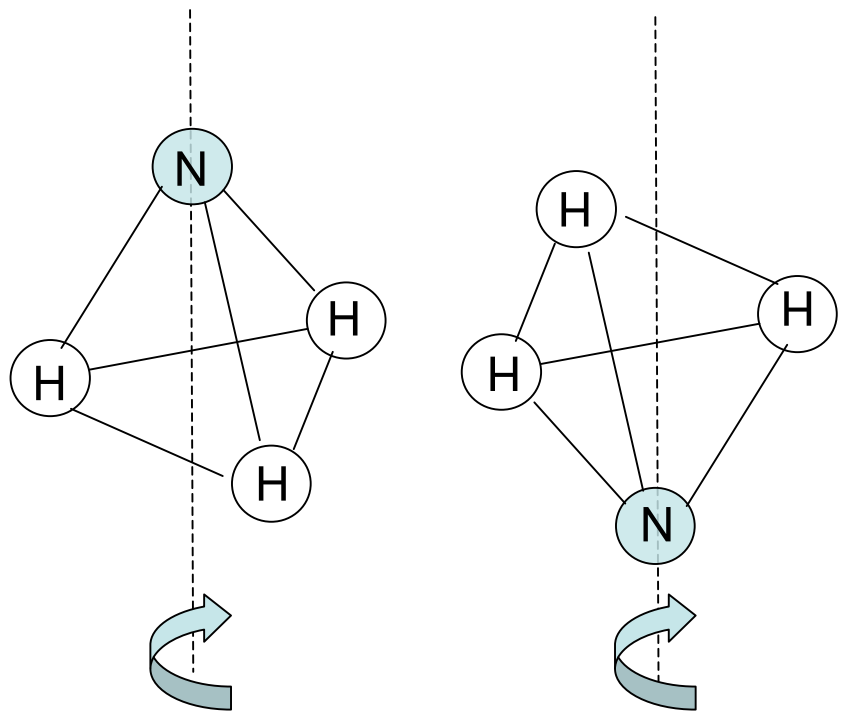
- The states are inherently long-lived

- So all you have to do is physically separate the high energy state from the low energy state to achieve a metastable population inversion

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3}$$

First maser

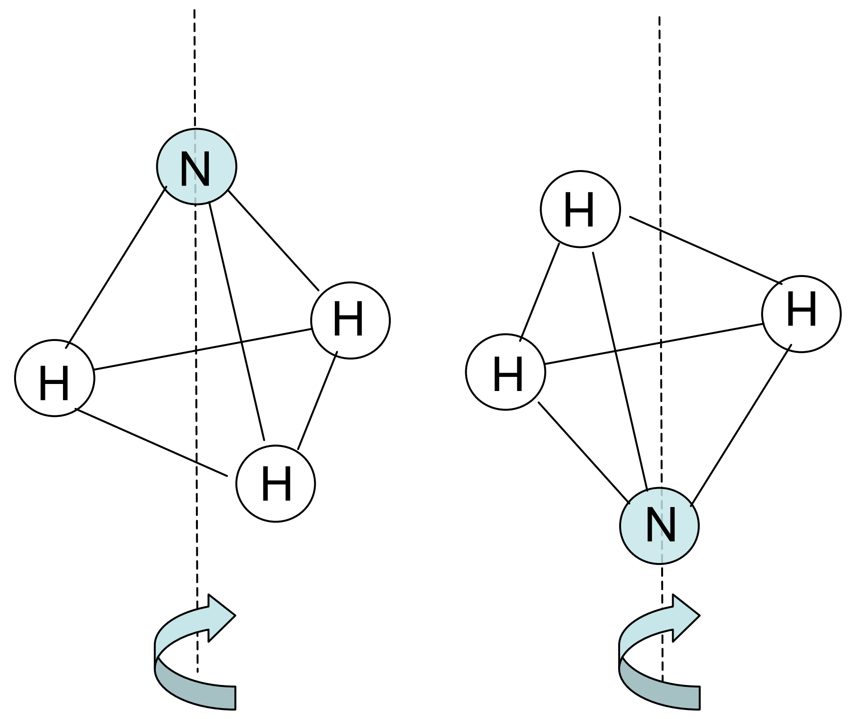
- The first maser was an ammonia-beam maser (1954)
- The two energy levels used in the ammonia maser are vibrational states of the ammonia molecule
- The hydrogen atoms can be considered to rotate
- The nitrogen atom oscillates between two positions, above and below the plane of the hydrogen atoms



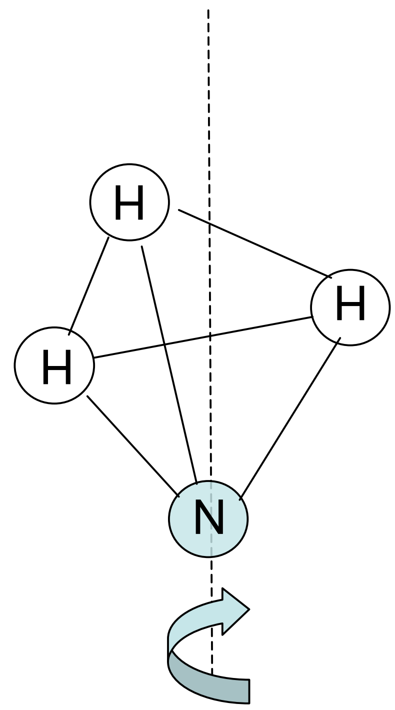
First maser

- These two arrangements do not represent exactly the same energy
- The wave functions of the hydrogen and nitrogen atoms are not quite symmetrical
- Therefore the molecule exists in two energy states
- The difference in energy between the states corresponds to a frequency difference of 23.87 GHz , or ~24 GHz

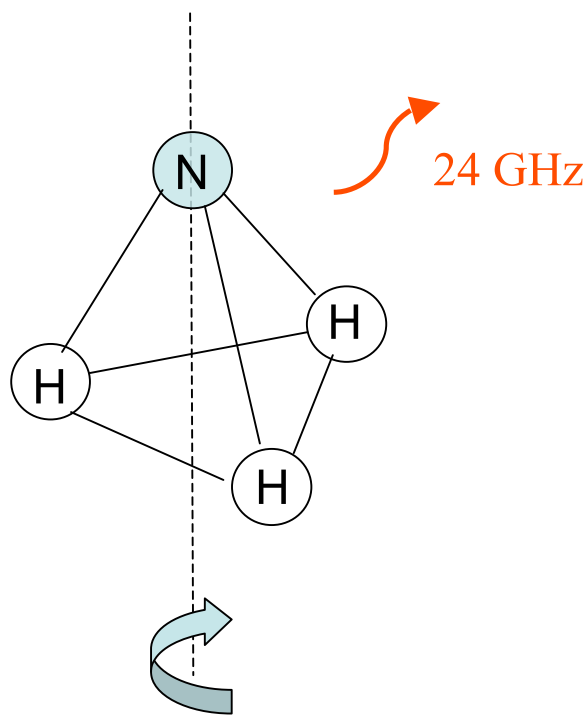
λ=1.25cm



First maser

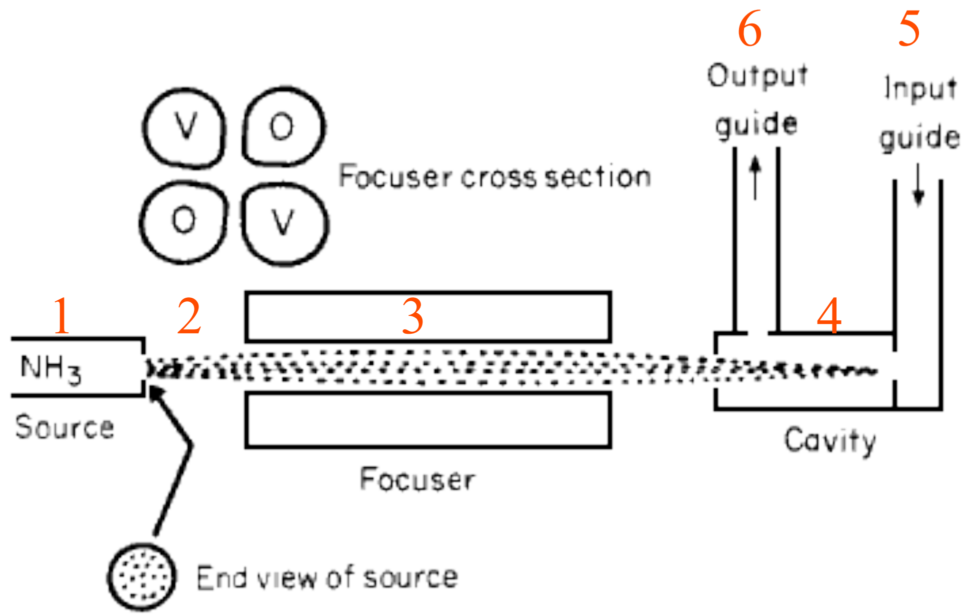


First maser



Ammonia-beam maser

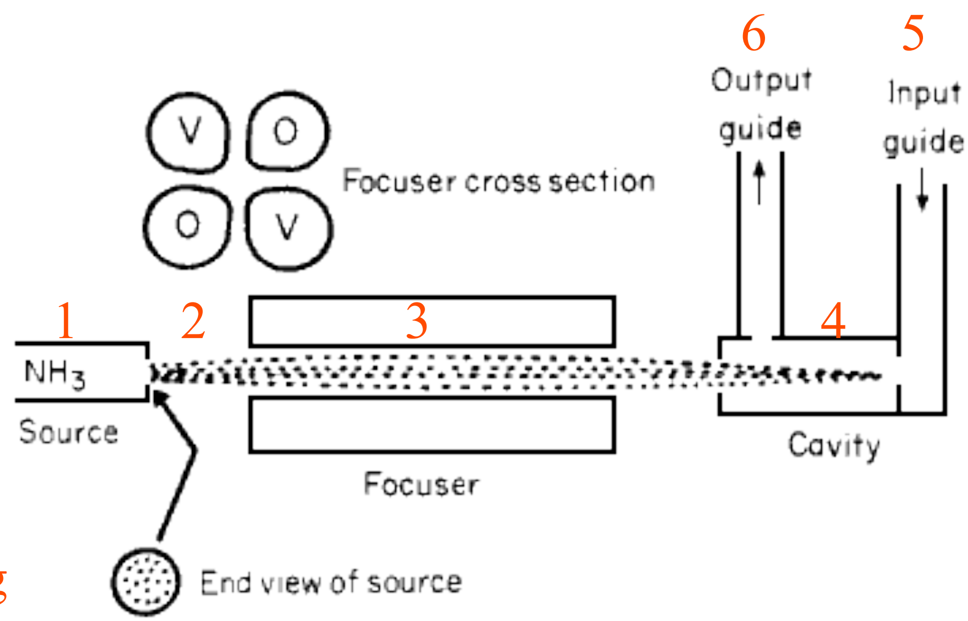
- 1. A heater gives energy to molecules of ammonia (NH_3) in the source
- At this point about half of the molecules are in an excited state, the other half are not.
- 2. The ammonia molecules stream into the focuser (also called a separator), which is evacuated.



Ammonia-beam maser

- 3. The focuser removes molecules in the lower quantum state from those in the upper quantum state (for these would absorb rather than emit photons at the desired frequency) while *focusing* those in the upper state

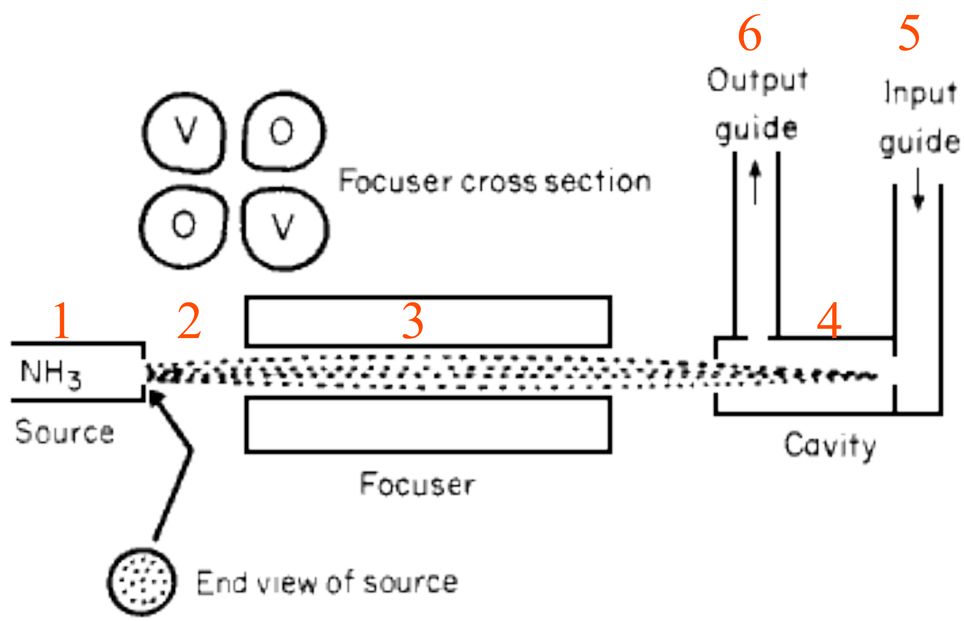
- The energy states can be *separated* by a system of focusing electrodes.



Ammonia-beam maser

- The electric dipole moments induced in the NH_3 molecules interact with the electric field produced by the electrodes

- The internal energy of an upper state molecule is increased and that of a lower state molecule is decreased so that, in the non-uniform electric field, the lower state molecules move towards the higher field region and the upper state molecules move to the lower field region



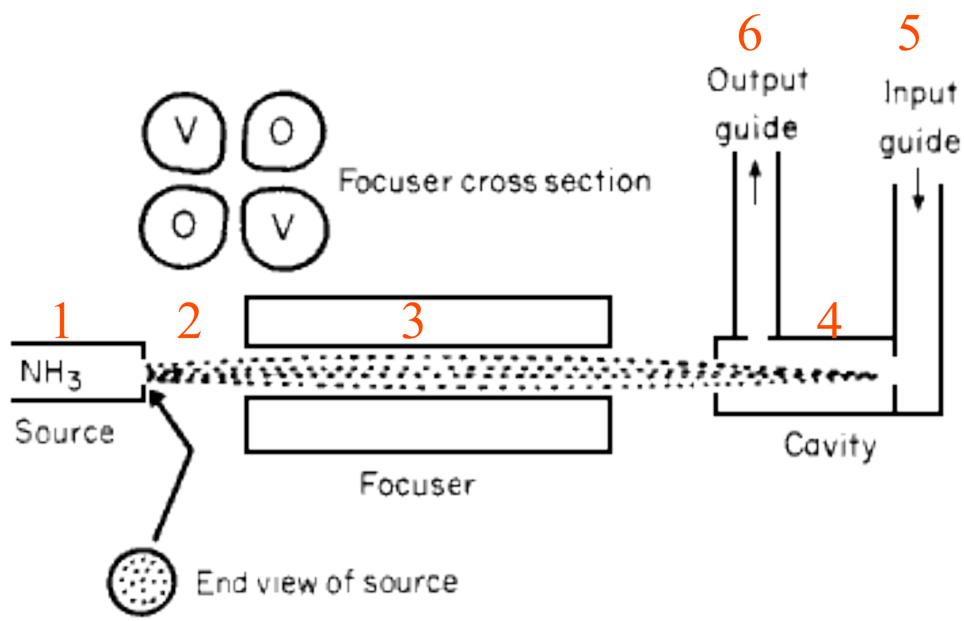
Ammonia-beam maser

- 4. The ammonia molecules that pass into the resonant cavity (tuned to 24GHz) are almost all excited

- They constitute an inverted population.

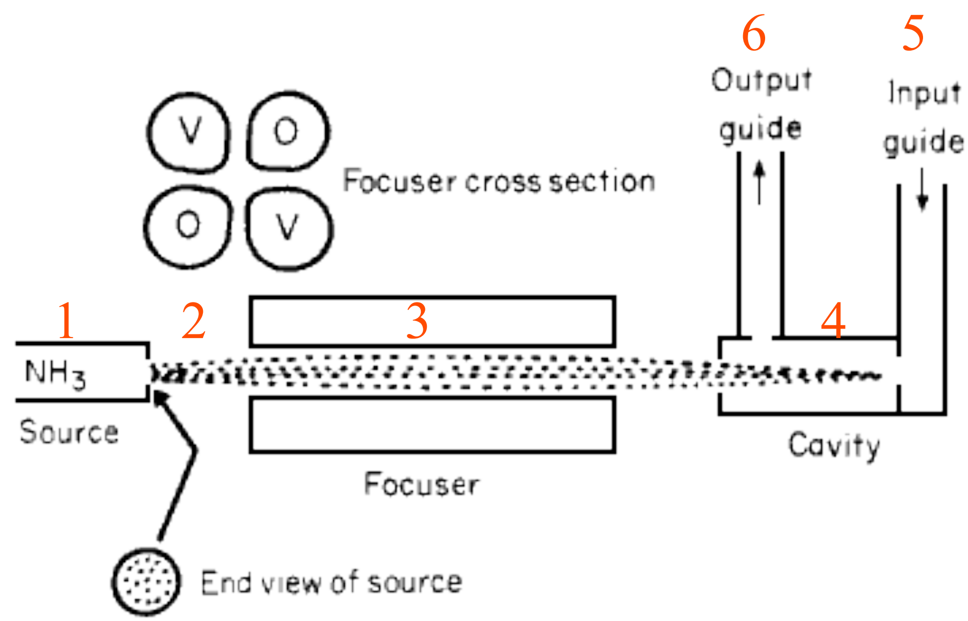
- The cavity has a very high Q, so there is sufficient noise power to initiate transitions from the upper state the lower state

- Photons from these transitions can then *stimulate* emission from other molecules.



Ammonia-beam maser

- 5. When it is used as an amplifier, the signal to be amplified is injected into the cavity that enter the cavity via an input waveguide
- This radiation leads to even more rapid stimulated emission by the excited molecules

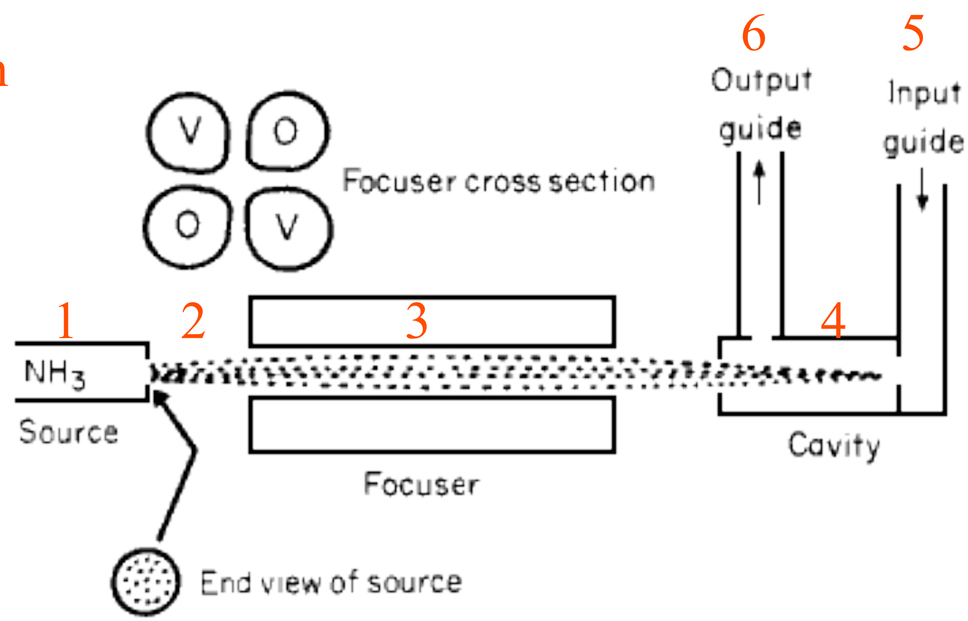


Ammonia-beam maser

- 6. The resultant coherent radiation detected at the output waveguide is an amplified version of the input signal

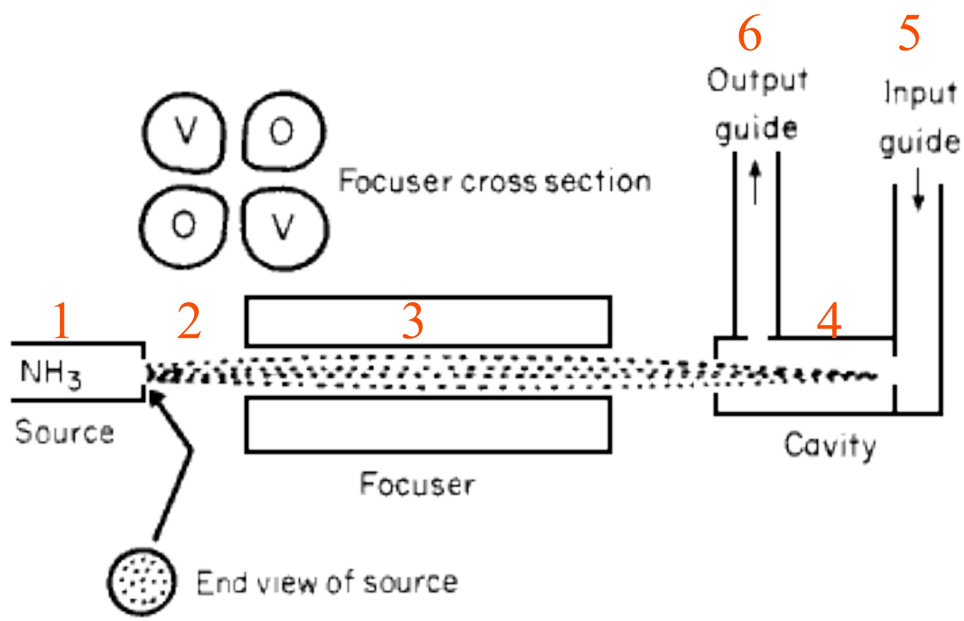
- Masers are low-noise amplifiers

- Since molecules are uncharged, the usual shot noise in electronic amplifiers is missing, and essentially no noise in addition to thermal noise is present in maser amplifiers



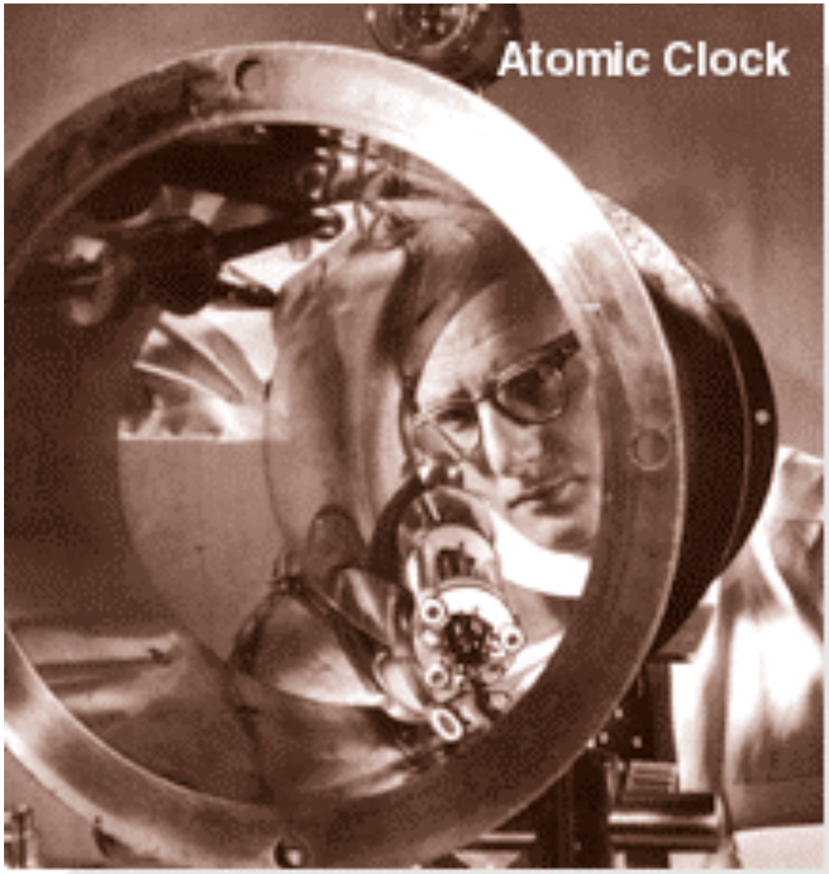
Ammonia-beam maser

- This radiation reflects back and forth inside the cavity, whose size is specially chosen and regulated to reinforce waves of just this frequency
- The maser is functioning as a self-oscillator



Ammonia-beam maser

- Such masers are extremely selective as amplifiers
- They will not amplify signals that are as little a 5000 Hz away from 24 GHz.
- They do not shift by more than one part on a billion or more over long periods, so the early masers were used as atomic clocks
- An NH_3-beam maser served as the first atomic clock standard by NIST (National Institute of Standards and Technology)



Solid state masers

- Gas molecules are not closely crowded together as they are the molecules of a solid, thus the power output of gas-beam masers remains low
- This inspired the development of solid state masers
- Pulsed solid state masers may be 2-state masers
- CW masers are generally 3-level systems

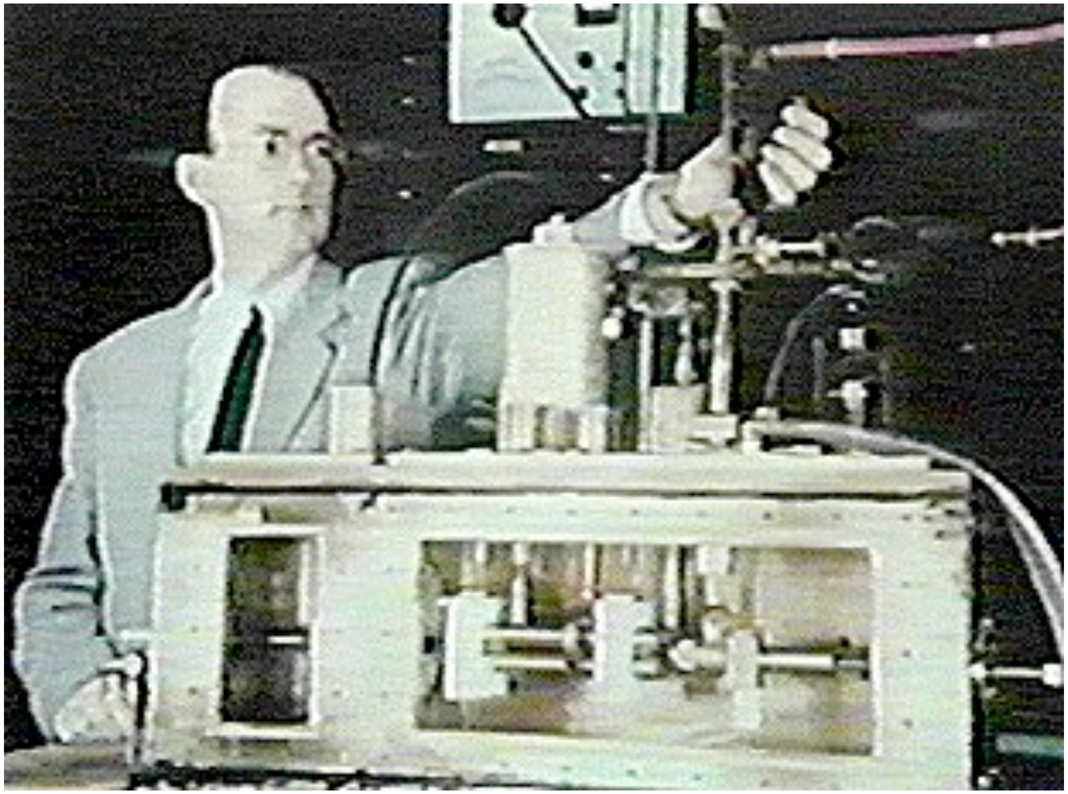
Nobel prize in 1964

"for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle"

		
Charles Hard Townes	**Nicolay Gennadiyevich Basov**	**Aleksandr Mikhailovich Prokhorov**
1/2 of the prize	1/4 of the prize	1/4 of the prize
USA	USSR	USSR
Massachusetts Institute of Technology (MIT) Cambridge, MA, USA	Lebedev Institute for Physics, Akademija Nauk Moscow, USSR	Lebedev Institute for Physics, Akademija Nauk Moscow, USSR
b. 1915	b. 1922 d. 2001	b. 1916 d. 2002

First maser?

- But was this really the first maser?



Charles Townes and the first manmade NH_3-beam maser

Astrophysical masers

- Naturally occurring molecular masers and lasers have been oscillating for eons in interstellar space, on comets, and in planetary atmospheres

Orion Nebula

Astrophysical masers

- In 1962, molecular lines detected in radio emission from interstellar clouds had huge intensities (equivalent to blackbody temperature of 10^{12}-10^{15} K) but at the same time had very narrow doppler linewidths (corresponding to kinetic temperatures below 100 K)

- An explanation is that these emissions represent naturally occurring masers

- Many types of astrophysical masers have been detected as OH, SiO, and H_2O

Orion Nebula

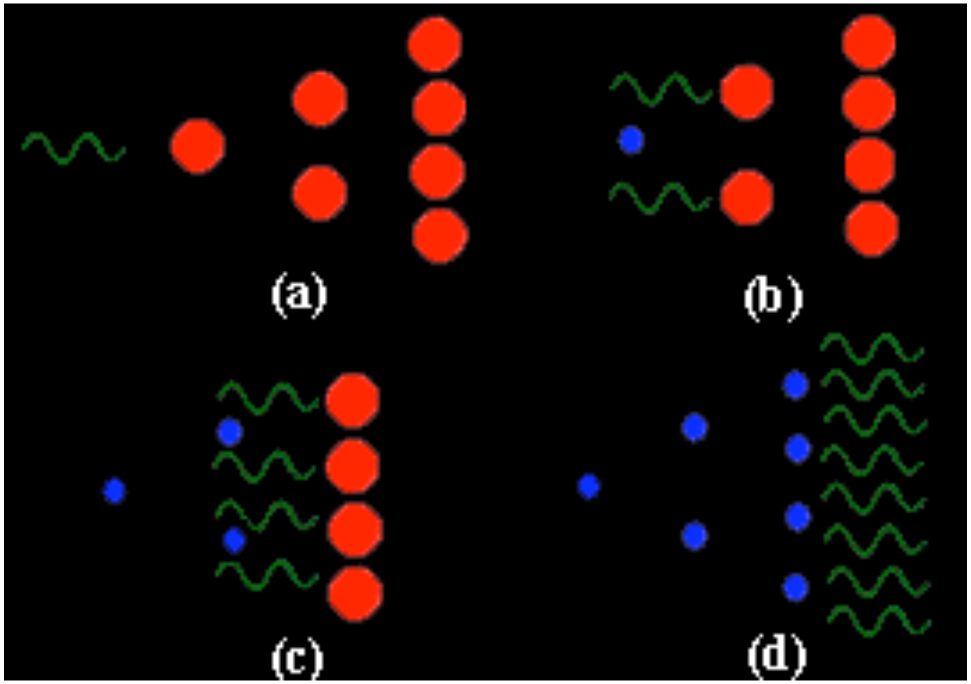
Astrophysical masers

- In colliding galaxies and near black holes, astronomical masers can be a million times stronger than regular masers
- These megamasers were discovered in 1982.

Orion Nebula

Conclusions

- Why were masers developed before lasers?
  - Because of the low energy of the microwave transitions
- How did the first maser work?
  - Physically separating a 2-state system of NH_3 molecule
- Applications?
  - Low noise amplifiers, oscillators, accurate clocks
- What were *really* the first masers?
  - Astrophysical masers!



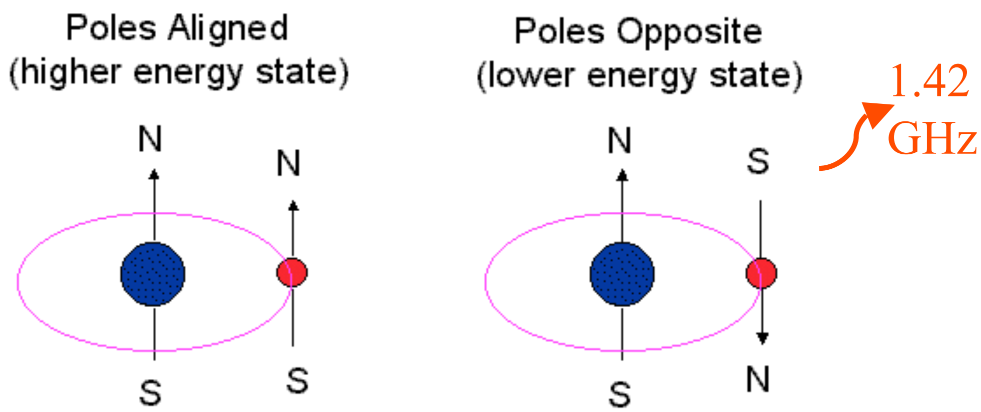
Hydrogen maser

- Another type of gas maser, using hydrogen rather than provides for an even more accurate clock

- The hydrogen maser uses another two-state system

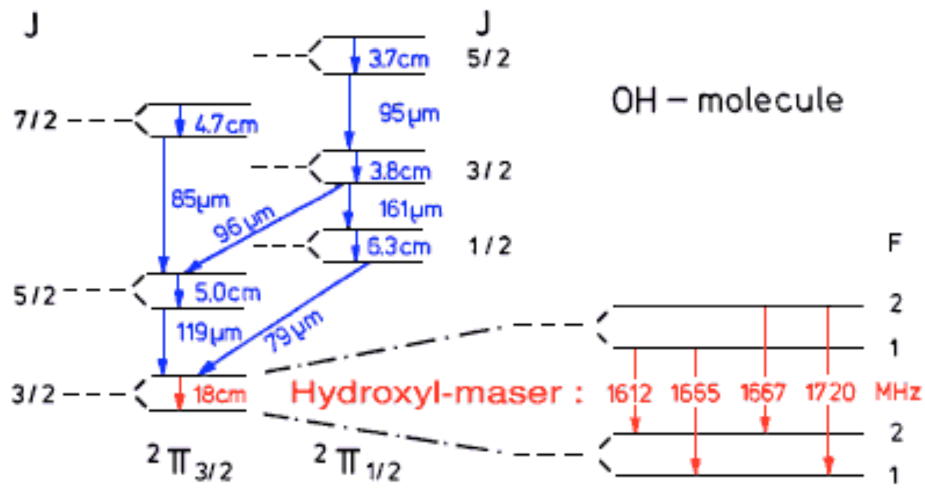
- A 21-cm photon is emitted when poles go from being aligned to opposite (a spin flip).

- This event only happens rarely for each H atom.



Interstellar OH

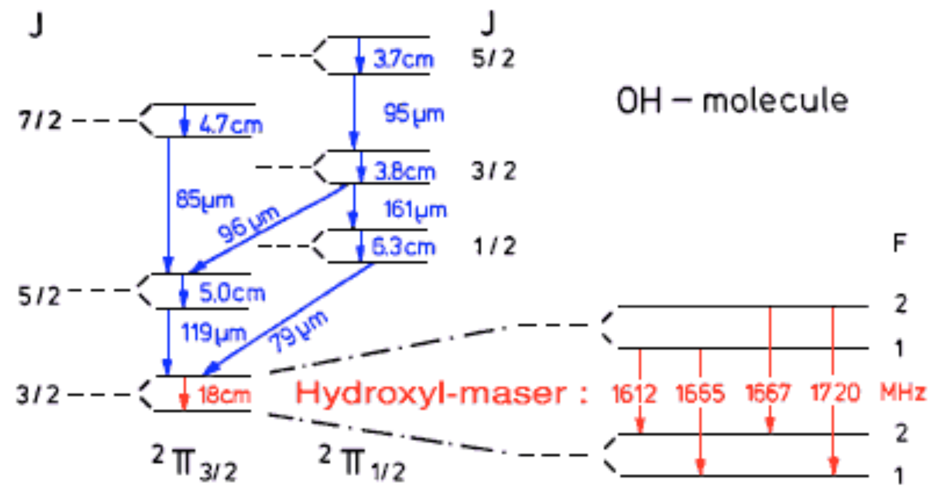
- OH was the the first radioastronomical observation of an interstellar molecule (1963)
- The identification was secure, because the 4 hyperfine splittings of 18-cm transition were detected at the relative strengths according to theory with the line ratios of 1612, 1665, 1667 and 1720 MHz being 1:5:9:1



Energy level diagram depicting the 18 cm microwave transition and its hyperfine structure

Astrophysical masers

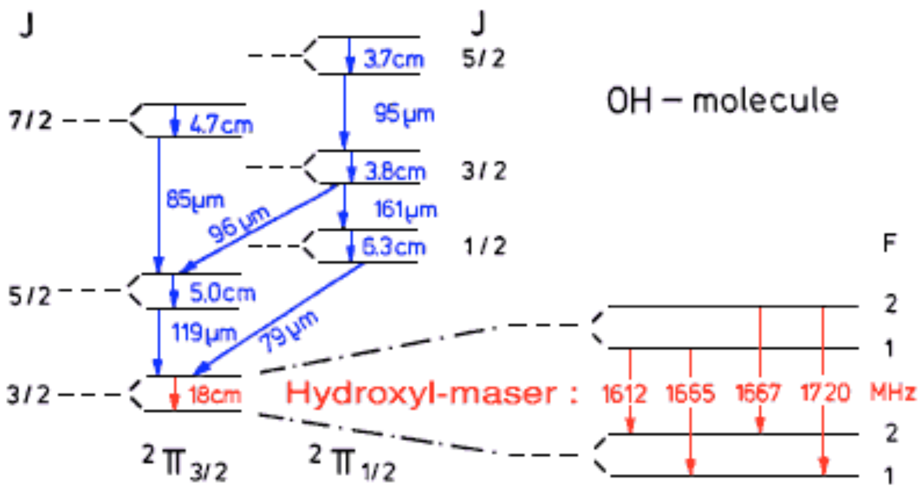
- Two years after he discovery of OH in radio absorption lines, OH was observed in emission
- The emission was of very high intensity, peculiar line-ratio strengths, very small line widths, and very high degrees of polarization, and varied on a timescale of days.
- The intensity was so high that if it arose from thermal processes, the temperature would have to be on the order of 10^{12} K!



Energy level diagram depicting the 18 cm microwave transition and its hyperfine structure

Astrophysical masers

- It is now believed that maser action causes the intense emission of OH.
- Since the discovery of OH masers, astronomers have discovered SiO masers,

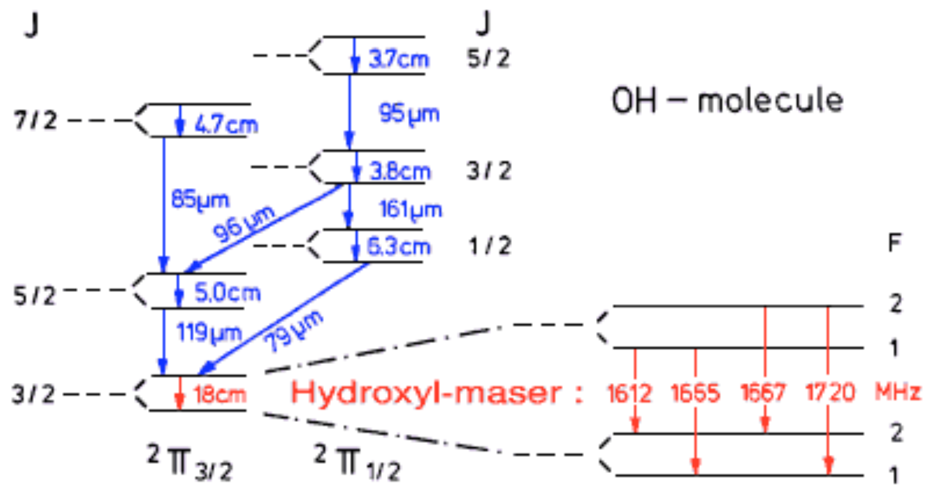


Energy level diagram depicting the 18 cm microwave transition and its hyperfine structure

Astrophysical masers

- Masers whose detailed modeling has been most successful are the OH masers in late-type stars that are pumped by infrared radiation resulting from the reemission of the stellar radiation by the dust particles that permeate the stellar wind.

- Detailed models of the H_2O masers in these sources show that pumping is controlled by collisions.



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